ASSESSING DWELLING VULNERABILITIES WITH CFD SIMULATIONS

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BARCELONATECH
Centre for Technological Risk Studies

Content

Introduction

WUI Fire Risk & Vulnerabilities

Many regulations exist to reduce fire risk at the microscale.

Often based on simple models & limited experiments.

May assume **flat ground, no wind, radiative heating only**

↳ Missing real fire exposure.

Need for better standards & guidelines using advanced fire engineering tools.

Safer buildings & well-managed properties depend on **improved vulnerability analysis.**

Performance-Based Design (PBD) in fire safety

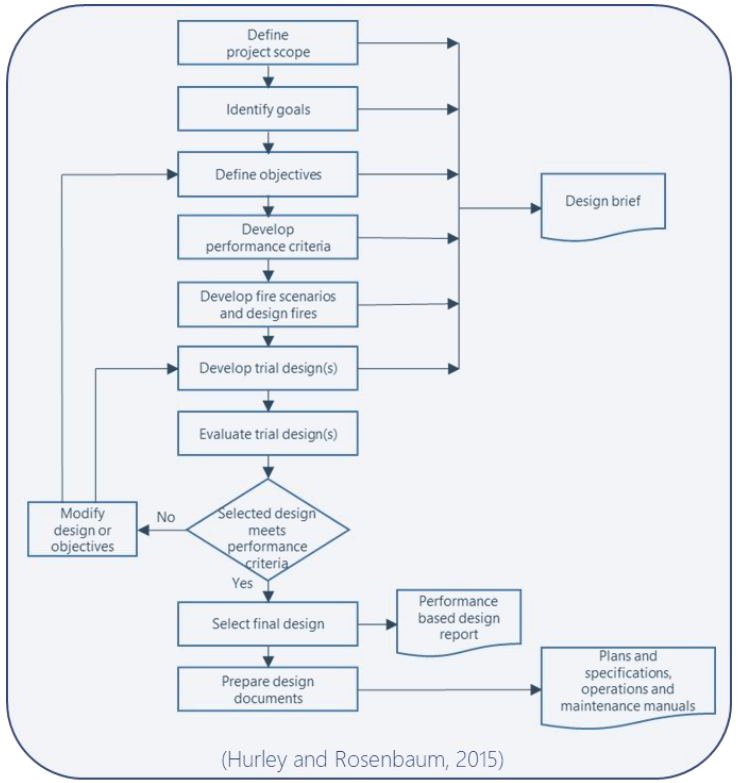
What is PBD?

A methodology ensuring fire safety by:

- ✓ Defining performance goals (life, assets, environment).
- ✓ Identifying **design fire scenarios** considering occupants, buildings & fire.
- ✓ Evaluating solutions using **CFD simulations** when needed.

Why use PBD?

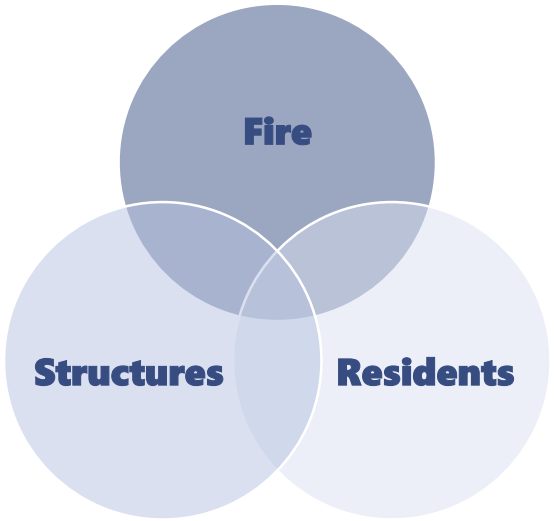
- Addresses challenges in **prescriptive codes** (e.g. high-rises, tunnels, green buildings).
- Supports **code updates** & advanced, goal-oriented regulations.
- Provides **clearer insights** on fire performance → better communication between stakeholders.



(Hurley and Rosenbaum, 2015)

The PBD approach at the WUI microscale

Why PBD at the property scale?



- ✓ Analyzes **fire-structure-resident interactions** in complex WUI scenarios.
- ✓ Regulatory bodies & researchers are adopting PBD, but **no specific guidelines exist** yet.

A WUI microscale PBD guideline has been developed

- Assesses both **new & existing buildings** under fire risk.
- Evaluates **current property state** & effectiveness of mitigation strategies (e.g. vegetation removal, fuel separation).
- Helps fire safety professionals **analyze risk** for life safety, property protection & resilience.
- Considers buildings as **both fire-resistant structures & safe shelters.**

The PBD approach at the WUI microscale

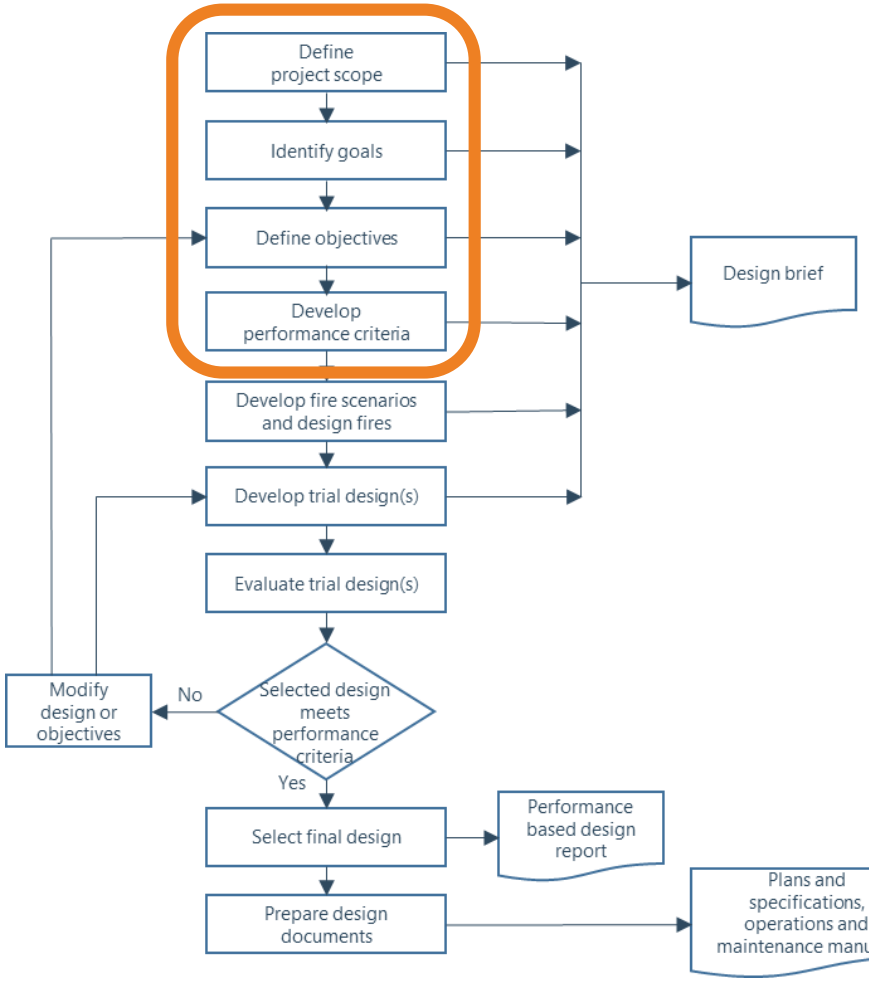
Scope & Goals

- ✓ Define the **fire safety challenge** specific to the WUI microscale.
- ✓ Identify whether the focus is **life safety** (sheltering/evacuation) or **property protection**.

Design objectives

Establish **measurable fire safety targets**, aligned with the identified goals:

- Protect **occupants** (sheltering vs. evacuation).
- Safeguard **structures** and reduce fire spread risk.
- Ensure **mission continuity** & environmental protection.



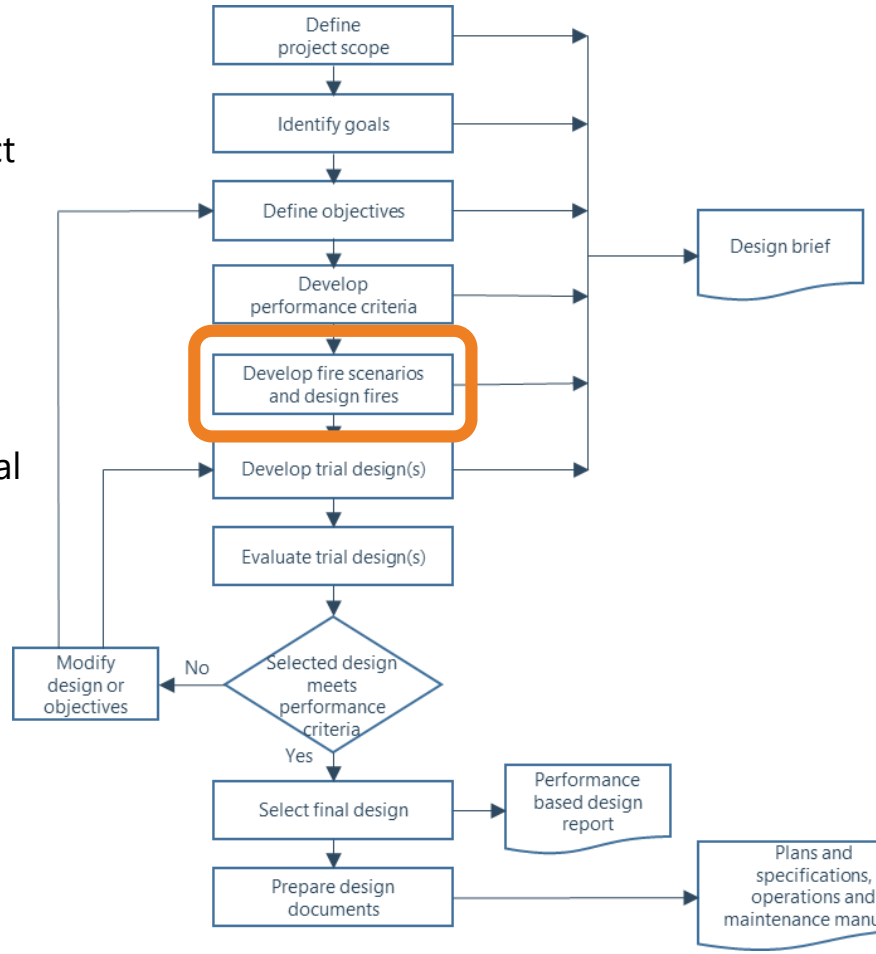
Performance criteria

- ✓ **Life safety criteria:** Assess sheltering capacity through tenability
- ✓ **Non-life safety criteria:** Evaluate building resilience to withstand

The PBD approach at the WUI microscale

Design fire scenarios

1. **High-frequency, low-consequence**
   - Likely events with minor property impact (e.g., ignition of a single fuel item).
   - Uses **average environmental conditions** (wind, humidity, temperature).
2. **Low-frequency, high-consequence**
   - Rare events with major damage potential (e.g., ignition of multiple fuels, hedgerows).
   - Assumes **extreme environmental conditions** (high winds, low humidity).
3. **Special Problems**
   - Unique site-specific risks (e.g., **LPG tanks, fuel storage in confined areas**).



Fire characteristics

Environmental characteristics

Building & Property characteristics

Occupant characteristics

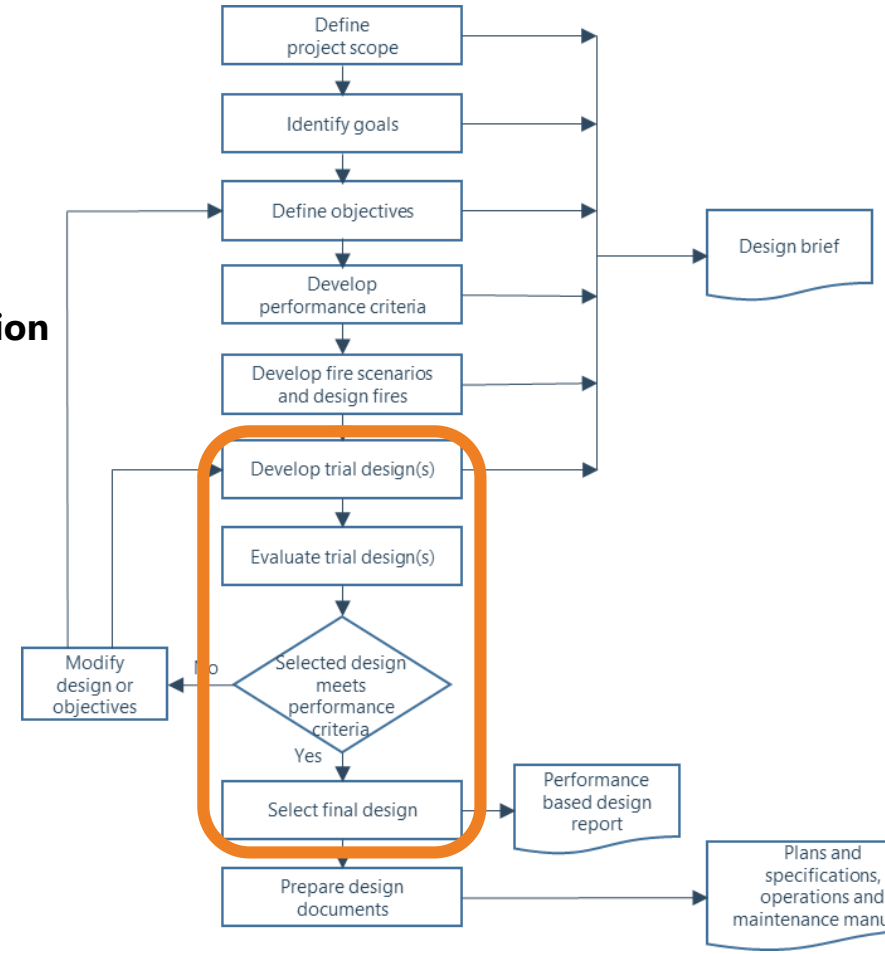
The PBD approach at the WUI microscale

Trial design

Assess vulnerabilities **as-is**.

Implement fire protection strategies:

- Reduce **ignition likelihood**
- Control **fire growth & spread**
- Apply **suppression & passive protection**



Trial design evaluation

- ✓ Determine if the design **meets performance criteria**.
- ✓ Use **fire modelling** for **quantitative** assessment.

CFD for WUI fire safety

- ✓ **FDS (Fire Dynamics Simulator)** enables detailed analysis.
- ✓ Captures **spatial & temporal variability** of WUI fire scenarios.
- ✓ Enhances **realistic assessment** of fire impacts & protection strategies.

WUI microscale CFD simulations

Application to a case study

Scope: entire property

Goal: property protection

Objectives:

- No structural damage
- No fire entrance

Building and property characteristics

- Concrete walls (15 cm)
- Non-combustible roof tiles
- Single pane glazing with PVC frame

Performance criteria: non-life safety

- Glass failure: $\Delta T < 83°C$
- Window frame failure (PVC): $T_{surface} < 220°C$
- Walls load bearing capacity: $\eta_{fi} > 74\%$

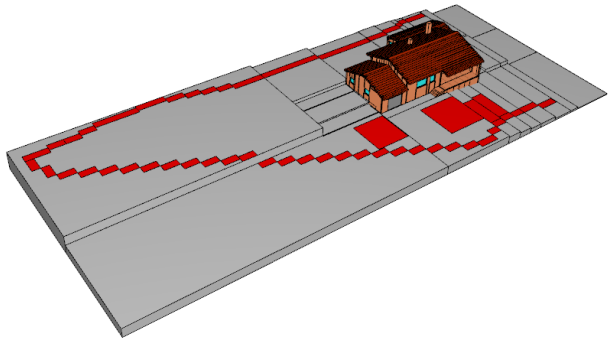
⚠ Difficulties in finding the right **performance criteria** and **data** !!

WUI microscale CFD simulations

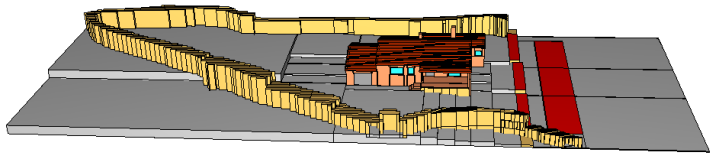
Application to a case study

Design fire scenarios

1. **High frequency – Low consequences**



2. **Low frequency-High consequences**



3. **Special problem**

⚠ Need of consensus to select proper design fire scenarios !!

Ignition in one point of the **hedgerow** located on the western side of the building and the subsequent **fire spread** towards the building.

Simultaneous combustion of the **trees and the hedgerow** located at the eastern side of the building.

Combustion of **outdoor furniture on the porch** with a big window with PVC.

WUI microscale CFD simulations

Application to a case study

How can we define fire characteristics in WUI environments?

3 types of fuels
- Ornamental vegetation
- Artificial fuels
- Wildland vegetation

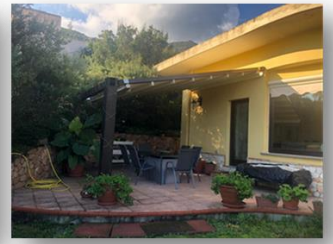
→ Lack of numerical data

→ Fireline intensity – semi-empirical approach


Stack of firewood


LPG tank


Hedgerow


Outdoor furniture


Ornamental vegetation

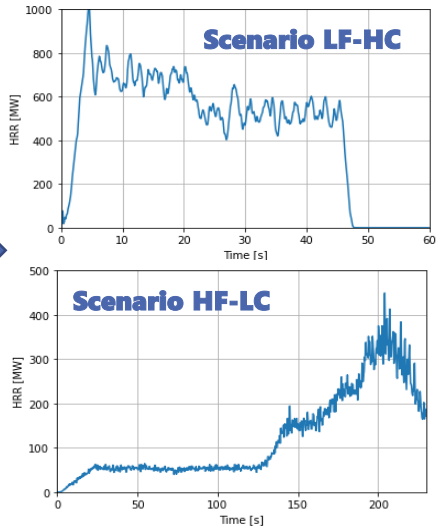
Vegetation

HRRPUA based on **fireline intensity** (I) and **flame depth** (D), calculated based on **rate of spread** (r - 10% of the wind speed) and **fuel consumption** (w)

$$I = Hwr$$

$$D = 0.39w^{0,25}u^{1.51}$$

Duration of the fire is based on the **residence time** (45 s for forests, 20 s for shrubs)

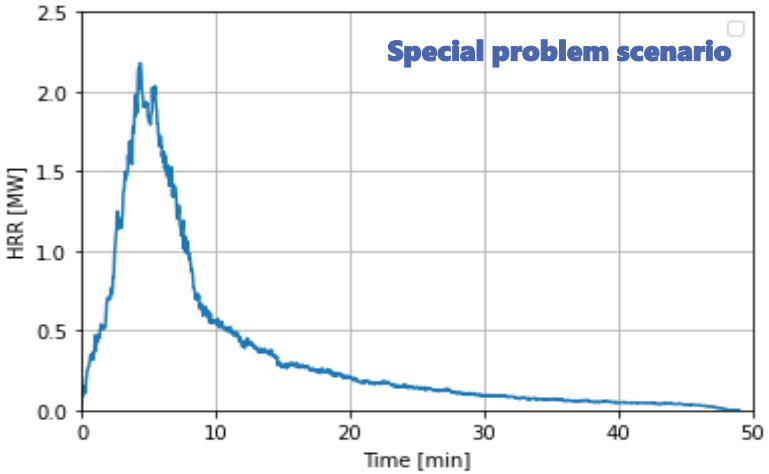


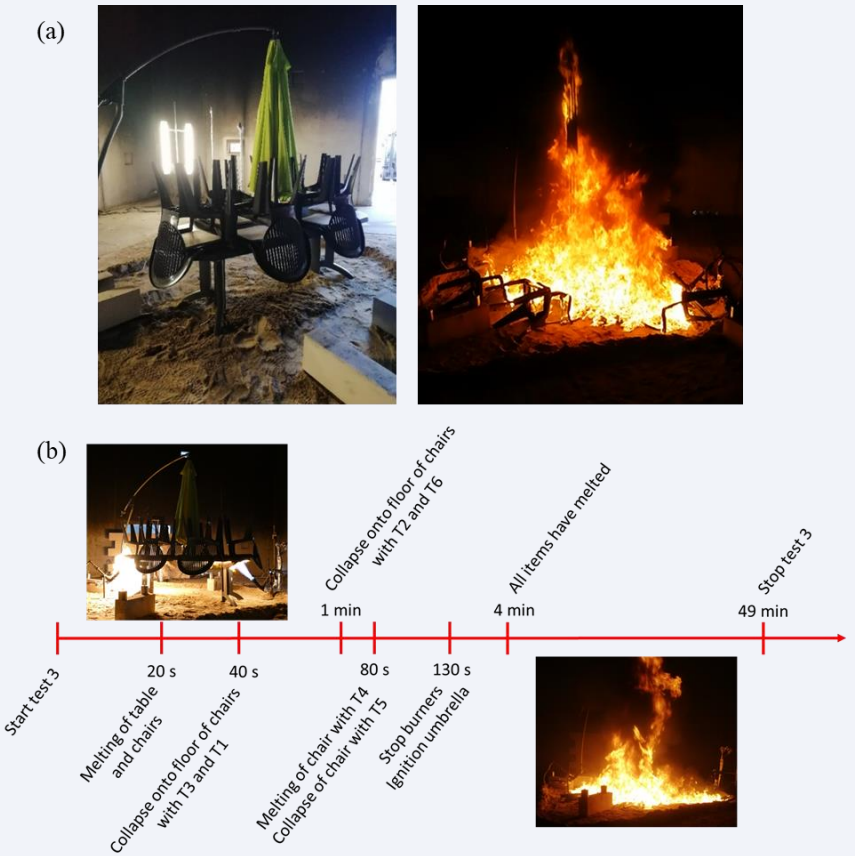
WUI microscale CFD simulations

Application to a case study

How can we define fire characteristics in WUI environments?

Porch furniture





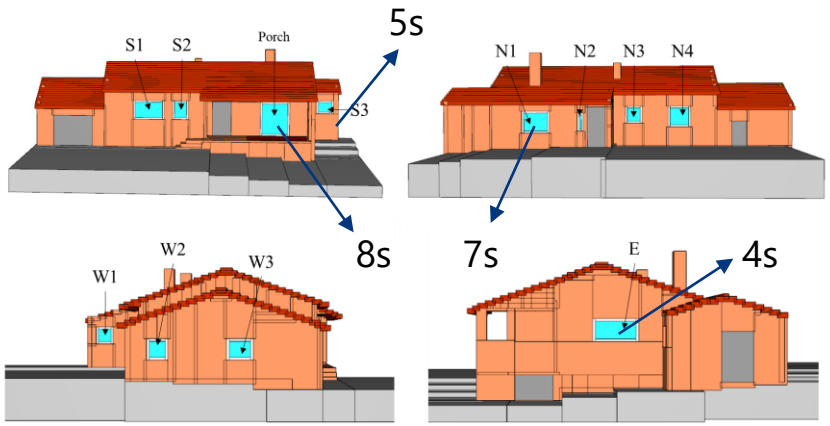
(Vacca et al., 2022)

WUI microscale CFD simulations

Application to a case study - Results

Scenario Low Frequency – High Consequences

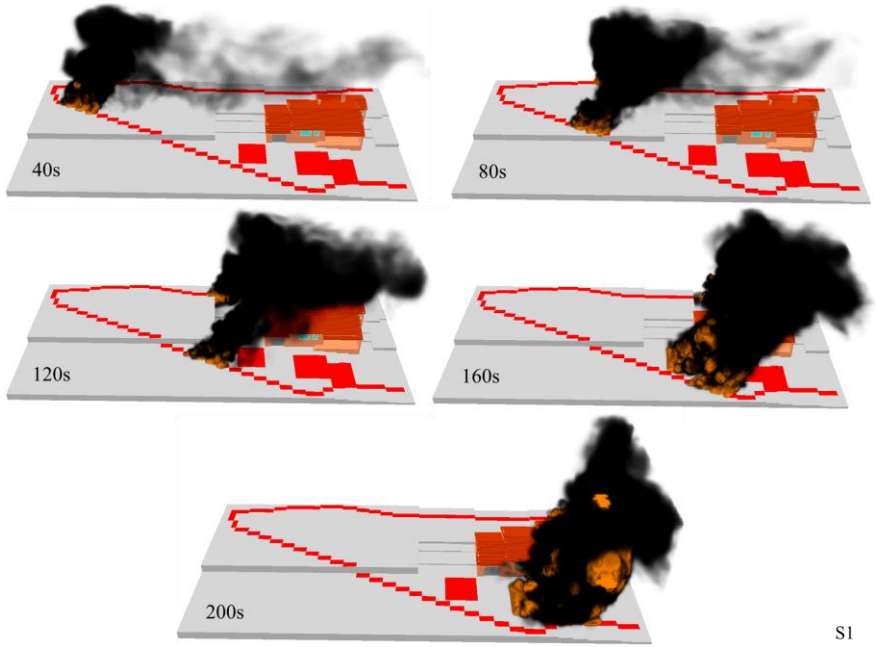
- Failure of 4 windows
  - ΔT and $T_{surf\ frame}$ are reached at the same time
- Wall's load bearing capacity does not drop



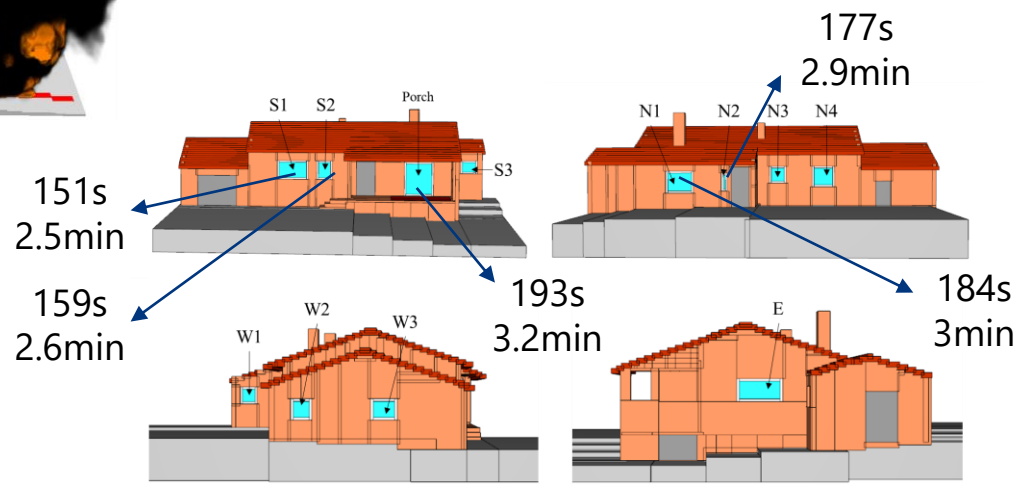
WUI microscale CFD simulations

Application to a case study - Results

Scenario High Frequency – Low Consequences



- Failure of 5 windows
  - First criterion that is met is the ΔT, followed a few seconds later by $T_{surf\ frame}$

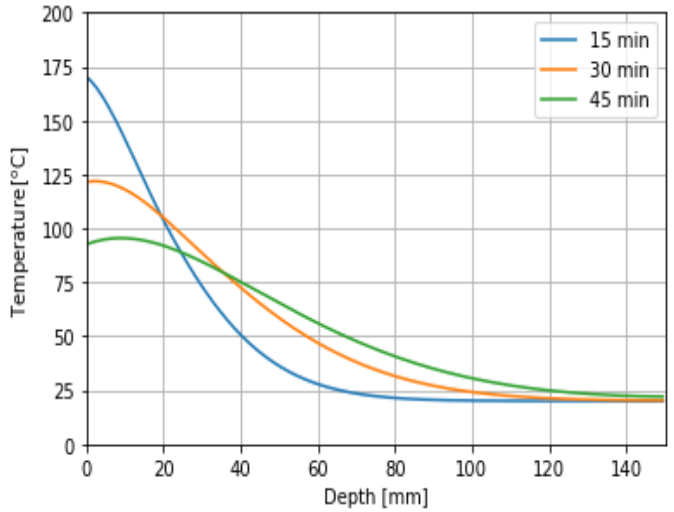


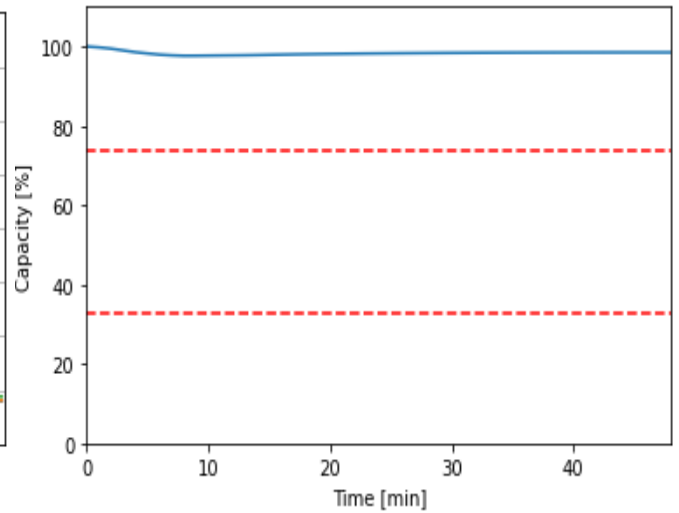
WUI microscale CFD simulations

Application to a case study - Results

Special problem scenario

- Failure of porch window
  - ΔT reached at 129s
  - $T_{surf\ frame}$ reached at 153s
- Wall's load bearing capacity does not drop



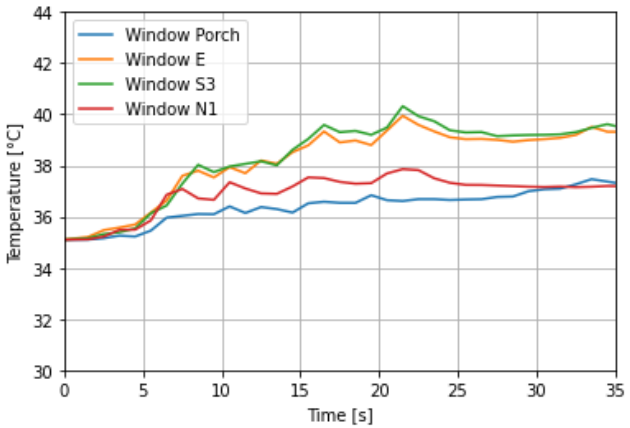


WUI microscale CFD simulations

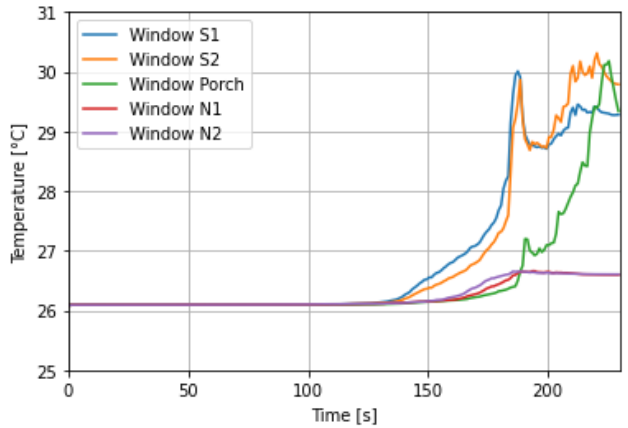
Application to a case study – Reducing vulnerability

Placing of solid aluminium shutters in front of glazing systems

Scenario LF – HC



Scenario HF – LC

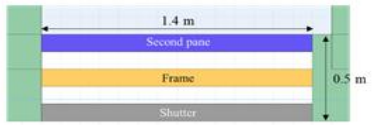


Performance criterion:
$T_{surf} < 660°C$

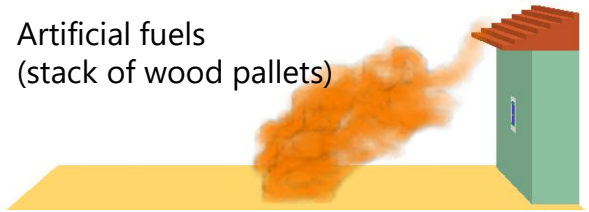
Sub-system analysis: combustion of fuels in the vicinity of glazing systems

Scenario variables:

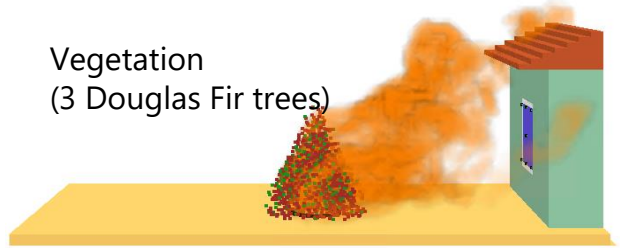
- Wind (30 km/h) and no wind
- Double glazing (3 mm and 6 mm panes)
- Two window sizes (0.5 x 0.5 and 1.2 x 1.2 m^2)
- Aluminium and PVC frame
- Aluminium, PVC and wooden shutters



Artificial fuels
(stack of wood pallets)



Vegetation
(3 Douglas Fir trees)



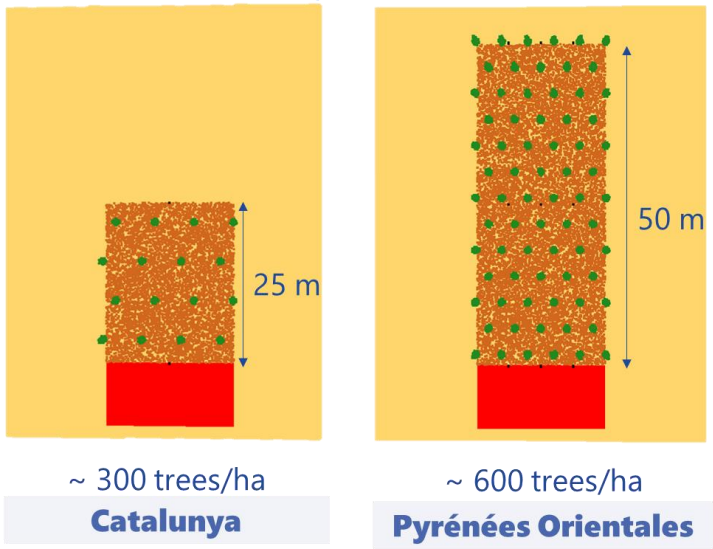
WUI microscale CFD simulations

Other applications

Quantitatively assess and compare the effectiveness of the prescriptions for **shaded fuel breaks** of Catalunya and Pyrénées-Orientales.

Quantify the effectiveness of current regulations and guidelines.

Top view



~ 300 trees/ha
Catalunya

~ 600 trees/ha
Pyrénées Orientales

Assessment of buildings **sheltering** capacity

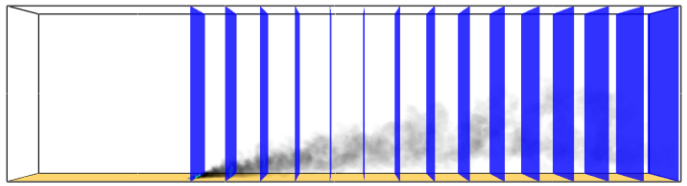
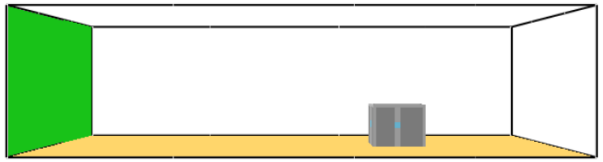
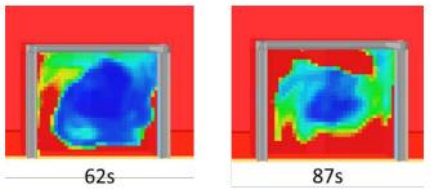


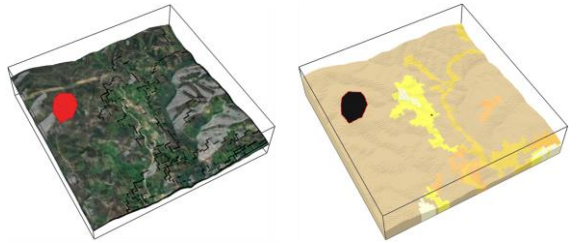
Figure 5-2: Domain of the wildfire smoke exposure simulation and location of slice files.





CO concentration inside the shelter.
Red means C>83 ppm (AEGL2)

WASET-WRSET (available and required safe egress time) for WUI evacuation/movement using FDS Level-set.



Implementation opportunities and challenges

Opportunities

- **Vulnerability Characterization** – Assess risks under diverse fire scenarios.
- **Safe Construction Guidelines** – Define fire-resilient building practices.
- **Vegetation & Structure Safety Distances** – Establish evidence-based buffer zones.
- **Fuel Break Design** – Develop adaptive models tailored to specific locations.
- **Building Sheltering Capacity** – Improve protection for occupants during fire events.
- **Forensic Fire Analysis** – Investigate past fires using PBD tools.
- **Engineering Adoption** – Promote PBD use in WUI projects (e.g., through SFPE).

Challenges

- **Lack of Regulations** – No specific PBD guidelines for WUI microscale.
- **Limited Data** – Insufficient fire behaviour data for ornamental vegetation & artificial fuels.
- **Computational Costs** – CFD simulations require significant resources & expertise.
- **Interdisciplinary Gap** – Need stronger collaboration between researchers, engineers & policymakers.
- **Standardization Issues** – Difficulty in integrating PBD into current codes & standards.
- **Stakeholder Awareness** – Fire safety professionals & regulators must be trained in PBD methods.

Take-away messages

✓ PBD is a powerful tool for WUI fire safety

- Allows **quantitative assessment** of fire risks at the **microscale**.
- Enhances **fire safety engineering approaches** beyond prescriptive rules.

✓ CFD simulations provide critical insights

- Help assess **building vulnerabilities & fire exposures**.
- Enable the **evaluation of fire mitigation strategies**.
- Support **evidence-based guidelines** for safe construction & land planning.

✓ Challenges remain for real-world implementation

- **Lack of regulations & standardized methods** for WUI PBD.
- **Data gaps** in fire behaviour of vegetation & artificial fuels.
- **Computational & expertise barriers** for widespread CFD adoption.

✓ Moving forward: collaboration is key

- **Research, engineering & policy** must align to integrate PBD into WUI fire management.
- Fire safety engineers (e.g., **SFPE**) should **embrace & promote these methods**.
- Need for **better data, models & training** to bridge current knowledge gaps.

Thank you

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